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## Nonperturbative contributions to a resummed leptonic angular distribution in inclusive $Z/\gamma^*$ boson production

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We summarize a new analysis of the distribution  $\phi_\eta^*$  of charged leptons produced in decays of  $Z$  and  $\gamma^*$  bosons in the Collins-Soper-Sterman (CSS) formalism for transverse momentum resummation. By comparing the  $\phi_\eta^*$  distribution measured at the Tevatron with the resummed CSS cross section with approximate  $\mathcal{O}(\alpha_s^2)$  Wilson coefficients, we constrain the magnitude of the nonperturbative Gaussian smearing factor and analyze its uncertainty caused by variations in scale parameters. We find excellent agreement between the  $\phi_\eta^*$  data and our theoretical prediction, provided by the RESBos resummation program. The nonperturbative factor that we obtained can be used to update resummed QCD predictions for precision measurements in inclusive  $W$  and  $Z$  production and for comparisons to various models of nonperturbative dynamics.

*Keywords:* Transverse momentum resummation; QCD Factorization

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**Leptonic angular distribution  $\phi_\eta^*$  as a probe of nonperturbative dynamics.** Precision of the current data from the Tevatron and LHC on the inclusive transverse momentum ( $Q_T$ ) distributions of  $W$  and  $Z$  bosons imposes growing demands on theoretical calculations.  $Q_T$  distributions are used for lucid tests of QCD factorization and in measurements of the  $W$  boson mass that place important constraints on the parameters of electroweak symmetry breaking. A variety of radiative contributions affect the  $Q_T$  distribution of a heavy boson at the current level of accuracy. They include NNLO QCD and NLO EW perturbative corrections, logarithmic QCD contributions that dominate  $d\sigma/dQ_T$  when  $Q_T \rightarrow 0$ , and also nonperturbative power-suppressed terms that modify the  $Q_T$  distribution when  $Q_T$  is below a few GeV. Collins, Soper, and Sterman (CSS) [1, 2, 3] have developed a QCD factorization approach to include all such terms order by order in  $\alpha_s$ . The

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CSS formalism combines the resummation of large Sudakov factors in the small- $Q_T$  limit [4, 5, 6] with fixed-order QCD contributions at large  $Q_T$ . As a recent development, the NNLL/NNLO expression for the resummed  $Q_T$  distribution has been published [7]. The CSS method is a classical realization of the factorization based on transverse-momentum dependent (TMD) distribution functions, in which PDFs and fragmentation functions depend explicitly on intrinsic transverse momentum in addition to the usual momentum fraction variables. While theoretical methods of TMD factorization [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19] and soft-collinear effective theory [9, 20, 8, 21, 22, 23] undergo rapid developments, the CSS formalism is well-suited for detailed phenomenological studies, as it is implemented in detail in practical simulations. In this short paper, we summarize a recent application of the CSS formalism for the computation of the angular distribution  $d\sigma/d\phi_\eta^*$  of the lepton pairs in  $Z/\gamma^*$  boson production at the Tevatron. Full details will be presented in a separate forthcoming paper [24]. The  $\phi_\eta^*$  distribution is closely related to the  $Q_T$  distribution in the limit  $\phi_\eta^* \propto Q_T/Q \rightarrow 0$ . Its analysis may provide valuable insights about the nonperturbative QCD dynamics.

The DØ collaboration has published detailed measurements of the  $\phi_\eta^*$  dependence in the electron and muon decay channels [25]. We ask if the DØ data corroborate the universal behavior of the resummed nonperturbative terms that was observed in the global analyses of  $Q_T$  distributions in  $\gamma^*$  and  $Z$  production at fixed-target and collider energies [26, 27]. We also investigate the rapidity dependence of the nonperturbative terms, which may be indicative of new types of higher-order contributions [28]. The small- $Q_T$  part of the distribution is obtained in the CSS formalism by the Fourier-Bessel transform of a form factor  $\widetilde{W}(b, Q)$  that depends on the transverse position variable  $b$ . For large boson virtualities  $Q$  of order 100 GeV, the overall form of the  $Q_T$  distribution *at all*  $Q_T$  is determined by small- $b$  contributions, arising at energy scales  $\mu \sim 1/b \gg 1$  GeV. Such contributions are entirely predicted in perturbative QCD theory. They dominate the cross section at any  $Q_T$  value [5, 29]. When  $Q_T$  is below 5 GeV, the production rate is also mildly sensitive to the behavior of  $\widetilde{W}(b, Q)$  at  $b > 0.5$  GeV<sup>-1</sup>, where the perturbative expansion is increasingly unreliable because of the vicinity of the Landau pole in  $\alpha_s(1/b)$ . We are interested to know which forms of the large- $b$  extrapolation of  $\widetilde{W}(b, Q)$  are compatible with the observed behavior of  $Q_T$  and  $\phi_\eta^*$  distributions. A comprehensive solution for  $\widetilde{W}(b, Q)$  at large  $b$  remains elusive, but efforts to derive it produced several instructive models, such as [30, 31, 32, 33, 34, 35, 20]. From the phenomenological point of view, a typical  $Z$  data set does not have sensitivity to distinguish between these models. In deeply nonperturbative region that is characterized by  $b \gtrsim 1$  GeV<sup>-1</sup>, the form factor  $\widetilde{W}(b, Q)$  is strongly suppressed and does not contribute to  $d\sigma/dQ_T$  for  $Q$  of order  $M_Z$  [27]. Only the contributions from the transition region of  $b$  of about 1 GeV<sup>-1</sup>, where  $\mu \approx 1/b$  is about 1 GeV, are numerically non-negligible compared to the leading-power cross section predicted by perturbative QCD theory. In the transition region, the extrapolation of the perturbative expres-

sion provides a reasonable approximation for the leading-power (logarithmic) part of  $\widetilde{W}(b, Q)$ . It can be realized in the “revised  $b_*$  model” [27], which parametrizes the extrapolated contribution by a flexible form that depends on a single parameter  $b_{max}$ . In addition, a few suppressed terms proportional to even powers of  $b$  play some role in this interval of  $b$ . In comparisons to the experimental data, their cumulative effect can be usually approximated by a single Gaussian smearing factor  $\exp\{-a(Q)b^2\}$ , where the coefficient  $a(Q)$  is found from the experiment. This arrangement provides a few-parameter approximation for viable nonperturbative models in the phenomenologically relevant region of  $b$ . In our previous work [27], the magnitude and  $Q$ -dependence of the Gaussian factor were determined from  $Q_T$  distributions of the Drell-Yan pairs. Recently, the  $\phi_\eta^*$  distribution has been proposed as a sensitive probe of the small- $Q_T$  dynamics [36], as it has reduced uncertainties associated with the lepton momentum resolution. Here we update the constraints on the Gaussian smearing factor in  $Z$  boson production using the  $\phi_\eta^*$  distribution.

Our analysis is carried out using the program RESBOS [37, 26, 38], which realizes the CSS formalism to compute fully differential cross sections of lepton pairs in production of high-mass virtual photons ( $\gamma^*$ ) and heavy electroweak bosons ( $W$ ,  $Z$ , and  $H$ ). A resummed treatment of new variables  $a_T$  and  $\phi_\eta^*$  and their relationship to  $Q_T$  was studied in [39, 40]. The fully differential output from RESBOS can also be cast in the form of the  $\phi_\eta^*$  distribution. In the new analysis, we find an excellent agreement between the RESBOS prediction and the  $\phi_\eta^*$  data, contrary to the conclusion made by the DØ paper [25]. However, the quality of agreement depends on the inclusion of perturbative loop contributions and selection of scales in the resummed cross section. In Refs. [39, 40, 41, 42, 7], the evidence for a nonzero nonperturbative factor in  $Z$  production has been contested in the light of the uncertainty in the resummed cross section due to the dependence on factorization scales. The evidence for nonperturbative smearing is inconclusive at the NLL+NLO level because of a large scale dependence. To address this point, we fully include the scale dependence in the small- $Q_T$  part of the resummed cross section up to  $\mathcal{O}(\alpha_s^2)$  [24]. Despite the scale uncertainties, the statistical analysis of the fit to the  $\phi_\eta^*$  data indicates pronounced preference for a nonperturbative Gaussian contribution with  $a(M_Z) \approx 1 \text{ GeV}^{-2}$ . The main reason is that the Gaussian suppression of the large- $b$  tail of  $\widetilde{W}(b, Q)$  alters the resummed  $d\sigma/dQ_T$  in a different way than the factorization scales in the leading-power part of  $\widetilde{W}(b, Q)$ . The nonperturbative Gaussian factor suppresses the rate only at  $Q_T$  below 2-3 GeV, while the leading-power scale dependence affects a broader interval of  $Q_T$  values. This results in a characteristic shift of the peak in the  $d\sigma/dQ_T$  distribution due to the nonperturbative suppression, which is distinct from the typical scale dependence.

**Particulars of the calculation.** In the CSS formalism, the full resummed (RES)  $Q_T$  distribution is commonly represented as a combination of the resummed

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(W), finite-order (FO), and asymptotic (ASY) terms [3]:

$$\left(\frac{d\sigma}{dQ_T^2}\right)_{RES} = \left(\frac{d\sigma}{dQ_T^2}\right)_W + \left(\frac{d\sigma}{dQ_T^2}\right)_{FO} - \left(\frac{d\sigma}{dQ_T^2}\right)_{ASY}. \quad (1)$$

The accuracy of the  $D\bar{O}$  measurement demands that the main perturbative corrections due to the QCD and electroweak radiation are included. Numerical, but not analytical, results for the complete NNLO QCD contribution to the resummed  $Q_T$  distribution in  $Z/\gamma^*$  production at the Tevatron have been recently released [7]. RESBOS includes the dominant NNLO QCD contributions and provides a faithful estimate for the remaining small NNLO contribution that has not been published in an analytical form, as summarized below. Thus, effectively RESBOS is close to the full NNLO precision in the kinematical region relevant for this analysis. The electroweak (EW) corrections to  $Z$  production compete in magnitude with NNLO QCD contributions and are available to NLO [43, 44, 45, 46]. In the comparison to the  $D\bar{O}$  data, we do not include the EW corrections in our theory prediction, but correct the fitted  $\phi_\eta^*$  data by subtracting the predominant correction due to the final-state photon radiation obtained by the PHOTOS code [47]. Upon the inclusion of these contributions, scale dependence remains a major systematic uncertainty affecting our theory prediction. In the latest RESBOS implementation, the fully differential CSS resummed cross section is given by [37]

$$\begin{aligned} \frac{d\sigma(h_1 h_2 \rightarrow (Z \rightarrow \ell\bar{\ell})X)}{dQ^2 dy dQ_T^2 d\Omega} &= \frac{1}{48\pi S} \frac{Q^2}{(Q^2 - M_Z^2)^2 + Q^4 \Gamma_Z^2 / M_Z^2} \\ &\times \left\{ \int \frac{d^2 b}{4\pi^2} e^{i\vec{Q}_T \cdot \vec{b}} \sum_{j=u,d,s,\dots} \tilde{W}_j^{pert}(b_*, Q, x_1, x_2, \Omega, C_1, C_2, C_3) \tilde{W}^{NP}(b, Q) \right. \\ &\left. + Y(Q_T, Q, x_1, x_2, \Omega, C_4) \right\}, \quad (2) \end{aligned}$$

in notations of Ref. [37]. The leading-power (“perturbative”) form factor  $\tilde{W}^{pert}$  is defined by

$$\begin{aligned} \tilde{W}^{pert} &= \sum_{j=u,d,s,\dots} |H(Q, \Omega, C_4)|^2 \exp \left[ - \int_{C_1^2/b^2}^{C_2^2 Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2} A(\bar{\mu}; C_1) \ln \left( \frac{C_2^2 Q^2}{\bar{\mu}^2} \right) + B(\bar{\mu}; C_1, C_2) \right] \\ &\times \sum_{a=g,q} [\mathcal{C}_{ja} \otimes f_{a/h_1}] \left( x_1, \frac{C_1}{C_2}, \frac{C_3}{b} \right) \sum_{b=g,q} [\mathcal{C}_{jb} \otimes f_{b/h_2}] \left( x_2, \frac{C_1}{C_2}, \frac{C_3}{b} \right), \quad (3) \end{aligned}$$

in terms of the hard part  $H(Q, \Omega, C_4)$  (dependent on  $Q$  and the solid angle  $\Omega = \{\theta_*, \varphi_*\}$  of  $Z$  boson decay in the Collins-Soper frame), Sudakov exponent, and convolutions  $[\mathcal{C}_{j/a} \otimes f_{a/H}]$  of Wilson coefficient functions  $\mathcal{C}_{j/a}(z, C_1/C_2, \mu_F = C_3/b)$  and parton distribution function  $f_{a/H}(z, \mu_F)$  for a parton  $a$  inside the initial-state hadron  $h$ .  $\tilde{W}^{NP}(b, Q)$  is the nonperturbative factor explained below.  $Y$  is the difference between the finite-order and asymptotic cross sections and it dominates at  $Q_T$  of order  $Q$ . Constants  $C_i$  (for  $i = 1, \dots, 4$ ) are the scale coefficients that

determine several factorization scales introduced by resummation. They arise because  $\tilde{W}^{pert}$  depends on two distinct momentum scales  $1/b$  and  $Q$ . Specifically,  $C_1 = b\mu$  and  $C_2 = \mu/Q$ , where  $\mu$  is the scale introduced by the evolution equations that control the large logarithms. The constant  $C_3$  arises in the Wilson convolutions  $[C_{j/a} \otimes f_{a/H}]$  and specifies the factorization scale  $\mu_F = C_3/b$  in the PDFs  $f_{a/H}(z, \mu_F)$ .  $C_4 = \mu_H/Q$  is the scale constant in the hard part  $H$  of the resummed term  $W$  and the  $Y$  piece, which we select as  $C_4 = C_2$  for simplicity. The expression for the resummed cross section becomes particularly simple for a “canonical” combination of the scale coefficients, given by  $C_1 = b_0$ ,  $C_2 = 1$ ,  $C_3 = b_0$ , where  $b_0 = 2e^{-\gamma_E}$ , and  $\gamma_E = 0.577\dots$  is the Euler–Mascheroni constant. We evaluate  $Y$  to  $\mathcal{O}(\alpha_s^2)$  based on the calculation in [48, 49, 50]. The functions  $A(\bar{\mu}; C_1)$  and  $B(\bar{\mu}; C_1, C_2)$  are computed up to orders  $\mathcal{O}(\alpha_s^3)$  and  $\mathcal{O}(\alpha_s^2)$ , respectively. The Wilson coefficient functions are computed exactly up to  $\mathcal{O}(\alpha_s)$ . The only unavailable part of the NNLO resummed cross section is the  $\mathcal{O}(\alpha_s^2)$  Wilson coefficient  $\mathcal{C}_{ja}^{(2)}$  which receives contributions from two loop virtual diagrams. However, from the fixed order NNLO calculation [50] this contribution is small in magnitude (2-3%), mostly affects the overall normalization of the  $W$  term, and has weak kinematical dependence. Thus, without losing accuracy, one can approximate this term by

$$\mathcal{C}_{ja}^{(2)}(z, C_1/C_2, C_3) = \delta\mathcal{C}^{(2)} \delta(1-z) \delta_{ja} + L(C_1, C_2, C_3), \quad (4)$$

where  $L(C_1, C_2, C_3) = 0$  for the canonical combination. Since  $\delta\mathcal{C}^{(2)}$  is nearly constant in the kinematical region relevant for  $Z$  production, we estimate its magnitude from the known value of the  $\mathcal{O}(\alpha_s^2)$   $K$ -factor for the inclusive cross section  $d\sigma/dQ$  that is known for a long time [51] and was evaluated in our analysis by the computer code CANDIA [52, 53]. The inclusion of the estimated  $\delta\mathcal{C}^{(2)}$  in the calculation has practically no effect on our conclusions. Finally,  $L(C_1, C_2, C_3)$  is found *exactly* by requiring the independence of the  $\alpha_s$  series expansion of  $\tilde{W}$  on the choice of  $C_1$ ,  $C_2$ , and  $C_3$  order by order. By truncating the series at  $\mathcal{O}(\alpha_s^2)$ , we must have the equality  $\tilde{W}(b, Q, C_1, C_2, C_3)|_{\mathcal{O}(\alpha_s^2)} = \tilde{W}(b, Q, C_1 = C_3 = b_0, C_2 = 1)|_{\mathcal{O}(\alpha_s^2)}$ , which allows us to completely reconstruct the dependence of the  $\mathcal{O}(\alpha_s^2)$  part on the scale parameters  $C_i$ . The dependence on the scale constants is illustrated in Fig. 1, which shows the ratio of the experimental and best-fit theoretical values of  $(1/\sigma) \cdot d\sigma/d\phi_\eta^*$  for electrons with a constraint  $|y_Z| \leq 1$  on the  $Z$  boson rapidity. The best agreement with the data are obtained for  $\{C_1 = 2b_0, C_2 = 1/2, C_3 = 2b_0\}$ . Several error bands are obtained by variations of the indicated scale parameters around this best-fit combination. The variation of the scales affects the quality of the fit quantified by  $\chi^2$  and modifies the cross section in a wide range of  $\phi_\eta^*$ . In contrast, the variation of the nonperturbative factor is pronounced only at  $\phi_\eta^* \lesssim 0.5$ , which corresponds to typical  $Q_T$  of a few GeV. This difference allows one to discriminate between the nonperturbative  $Q_T$  smearing and perturbative scale dependence.

**The nonperturbative factor.** In order to extrapolate  $\tilde{W}^{pert}$  in Eq. (2) to the large  $b$  values of order or above  $1 \text{ GeV}^{-1}$ , we evaluate it in the revised  $b_*(b, b_{max})$  model [27] as a function of  $b_* \equiv b/\sqrt{1 + (b/b_{max})^2}$  with  $b_{max} = 1.5 \text{ GeV}^{-1}$ .

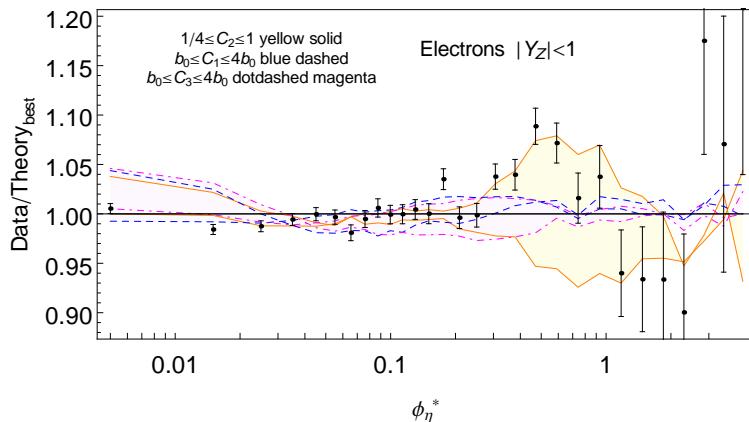


Fig. 1. Impact of the scale variation on the agreement between theory and data for  $|y_Z| \leq 1$ .

The factorization scale in the convolutions  $[C \otimes f]$  is set in this model to  $\mu_F = C_3/b_*(b, b_0/Q_0)$ , where  $Q_0 = 1$  GeV is the initial scale of the PDFs. This choice of  $b_{max}$  is preferred by the global fit to Drell-Yan  $Q_T$  data, where it both improves the agreement with the data and preserves the exact form of the perturbative expansion for  $\tilde{W}^{pert}$  at  $b < 1$  GeV $^{-1}$ . The  $\phi_\eta^*$  data is dominated by the narrow vicinity of  $Q$  around  $M_Z$ . Therefore, for the purpose of this analysis, it suffices to approximate the nonperturbative Gaussian factor as

$$\tilde{W}^{NP}(b, Q \approx M_Z) = \exp[-a_1(M_Z) b^2]. \quad (5)$$

This expression simplifies a more general parametrization [27, 26]

$$\tilde{W}^{NP}(b, Q) = \exp\left[-b^2 \left(a_1 + a_2 \ln\left(\frac{Q}{Q_0}\right) + a_3 \ln\left(\frac{x_1 x_2}{0.01}\right)\right)\right], \quad (6)$$

in which the coefficients  $a_1$ ,  $a_2$ , and  $a_3$  can be separated by fitting to several data sets at distinct  $\sqrt{s}$  and  $Q$  combinations. Once  $a_1(M_Z)$  is known, the coefficients  $a_2$  and  $a_3$  from the global  $Q_T$  fit of Ref. [27] can be used to find  $\tilde{W}^{NP}$  in  $W$  boson production. In each  $y_Z$  bin of the electron and muon  $\phi_\eta^*$  data, we compute  $\chi^2$  and use it to determine the nonperturbative coefficient  $a_1$ . The results are shown in Fig. 2. In order to estimate the impact of the scale dependence, the fit includes a correlation matrix quantifying the uncertainty in the theory cross section due to variations in the scale constants  $C_1$ ,  $C_2$  and  $C_3$ . In this case, we assign the 68% confidence to the interval  $-1 \leq \log_2(C_i/C_i^{best-fit}) \leq 1$ . According to the figure, all rapidity bins generally prefer a non-zero  $a_1$ , even if the scale shifts are included. The scale dependence increases the errors and makes them very asymmetric, but a downward change in the best-fit  $a_1$  is more disfavored than the upward change. With the scale shifts, we obtain the central value of  $a_1(M_Z) = 1.08^{+0.44}_{-0.43}$  GeV $^{-2}$ . No

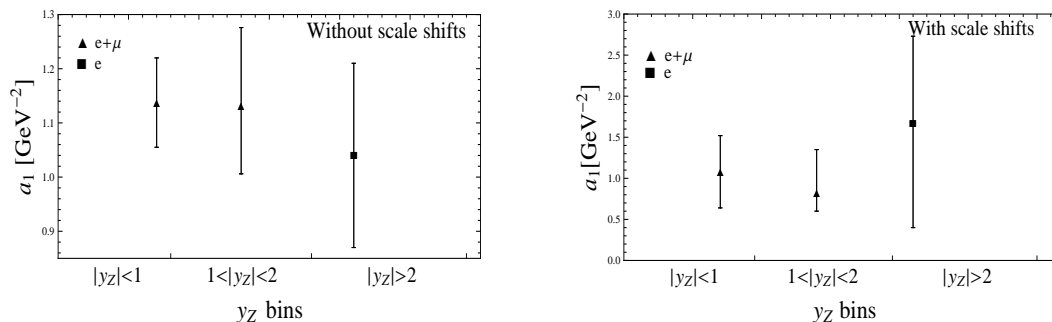


Fig. 2. Estimate of coefficient  $a_1$  in the three bins of rapidity of the data without (left inset) and with (right inset)  $C_1, C_2$  and  $C_3$  shifts.

significant dependence of the best-fit  $a_1(M_Z)$  values on the rapidity  $y_Z$  is observed, but the uncertainty is very large in the  $|y_Z| > 2$  bin.

**Conclusions.** A new version of the resummation program RESBOS was employed to examine the differential cross section at small values of the leptonic angle  $\phi_\eta^*$  at the Tevatron. The data on the  $Z/\gamma^*$   $\phi_\eta^*$  distribution collected by the DØ collaboraton was compared with the CSS resummed cross sections with approximate  $\mathcal{O}(\alpha_s^2)$  Wilson coefficient functions and complete  $\mathcal{O}(\alpha_s^2)$  scale dependence. RESBOS agrees well with these data, provided we use the hard scales  $Q/2$  (i.e., the scale coefficients  $C_2 = C_4 = 1/2$ ) in the resummed cross section. We determined the nonperturbative factor  $\widetilde{W}^{NP}(b, Q)$  preferred by the  $\phi_\eta^*$ , while evaluating the effects that have comparable magnitude: QCD scale dependence at  $\mathcal{O}(\alpha_s^2)$  and NLO electromagnetic contributions. In a fit that allowed for variations of the resummation scale parameters  $C_i$ , we observe a  $2.5\sigma$  preference for a non-zero Gaussian smearing factor  $a_1(M_Z) \approx 1.1 \text{ GeV}^{-2}$ . This central value is in agreement with the findings of the previous analyses of  $Z$   $Q_T$ -dependent distributions [33, 35, 27]. The non-perturbative factor  $\widetilde{W}^{NP}(b, Q)$  is a part of the complete resummed factor  $\widetilde{W}^{pert}(b_*, Q)\widetilde{W}^{NP}(b, Q)$ , which is well-constrained in the phenomenologically relevant region  $b \lesssim 1 \text{ GeV}^{-1}$  by a combination of the  $\mathcal{O}(\alpha_s^2)$  PQCD calculation and the nonperturbative factor found from the experimental data. Further information on this study will be provided in Ref. [24]. It will be used to update RESBOS predictions for future Tevatron and LHC studies.

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